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Safety assessment of dual shear wall-frame structures subject to Mainshock-Aftershock sequence in terms of fragility and vulnerability curves

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Abstract. Successive ground motions having short time intervals have occurred in many earthquakes so far. It is necessary to investigate the effects of this phenomenon on different types of structures and to take these effects into consideration while designing or retrofitting structures. The effects of seismic sequences on the structures with combined reinforced concrete shear wall and moment resisting frame system have not been investigated in details yet. This paper has tried to analyse the seismic performance of structures with such structural systems subjected to mainshock-aftershock sequences. The effects of the seismic sequences on the investigated models are evaluated by strong measures such as IDA capacity and fragility and vulnerability curves. The results of this study show that the seismic sequences have a significant effect on the investigated models, which necessitates considering this effect on designing, retrofitting, decision making, and taking precautions.

Keywords: safety; aftershock; shear wall; reinforced concrete; vulnerability

1. Introduction

Moderate to strong aftershocks usually follow moderate to strong earthquakes. For example, successive mainshock-aftershocks (MA-AF) with a moment magnitude of 6.4 and 4.9 respectively occurred at interval of 6 minutes in Ahar (Iran) in 2012. Aftershocks usually occur after a short interval, so there is not enough time to repair damaged structures before the occurrence of aftershocks. Therefore, aftershocks may greatly increase the cumulative damage of structures. Neglecting the effects of aftershocks on the structures design may lead to severe economic damage and great loss of life. Sometimes, landlords have to replace their buildings because of great residual deformation which occurs during the seismic sequence. Thus it is necessary to study the performance of the structures that are exposed to seismic sequences. The first study on the aftershocks was conducted by Omori in the field of seismology (Omori 1895). Moreover, García (García 2012) investigated 184 real MA-AF sequences. Her studies showed that mainshocks have a longer predominant period in comparison with corresponding aftershocks and the response of damaged structures to aftershock depends on the predominant period of aftershock strongly. Moreover, researchers have investigated seismic sequences effects on different types of structures such as bridge, steel and RC moment frame, etc. In the following, some previous studies on the effects of the seismic sequences on the structures are mentioned, which fall into two categories: the studies on SDOF systems and the studies on MDOF systems. For the first time, Mahin in 1980 investigated the effects of the seismic sequences on the SDOF systems. He showed that the aftershocks may increase cumulative damage; they may even lead to the collapse of structures (Mahin 1980). Sunsaka *et al.* investigated the damage spectrum of SDOF structures and proposed a method to evaluate the strength demand spectra of a structure subjected to seismic sequences (Sunsaka *et al.* 2002). Amadio *et al.* evaluated a set of SDOF systems with variant hysteretic models under repeated earthquakes. The results of this study show SDOF systems with elastic-perfect plastic are the most vulnerable systems under seismic sequence (Amadio *et al.* 2003). Das *et al.* proposed a method to limit the cumulative damage of structures subjected to seismic sequences by increasing the yield strength of the SDOF systems (Das *et al.* 2007). Hatzigeorgiou and Beskos carried out extensive parametric studies on SDOF models and proposed an equation to calculate the nonlinear to linear displacement ratio. Their investigation showed that the nonlinear displacement of SDOF structures may increase up to 100% under seismic sequences (2009). Hatzigeorgiou proposed an equation for the ductility demand based on 120 million dynamic inelastic analyses, considering the seismic sequences effects (Hatzigeorgiou 2010). Additionally, he suggested an equation to estimate the behavior factor by carrying out 2612400 nonlinear time history analyses of 8400 SDOF models under the 3110 near-fault earthquakes. Her study showed that under consecutive earthquakes, the behavior factor is smaller and ductility demand is greater (Hatzigeorgiou 2010). Also Hatzigeorgiou *et al.* proposed a relation to predict the maximum displacement of damaged structures under aftershocks by using residual displacement after the occurrence of the mainshock (Hatzigeorgiou *et al.* 2011). The proposed method can be used for steel or concrete structures subjected to far or near field earthquakes. Sarno' studies on the SDOF systems in 2013

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showed that seismic sequences may increase force demand up to thrice (Sarno 2013). Moustafa and Takewaki proposed a stochastic model to generate artificial seismic sequences and investigate nonlinear response of SDOF structure to successive earthquakes (Moustafa and Takewaki 2011). Goda studied the effects of seismic sequences on ductility demand (Goda 2012). Zhai *et al.* carried out extensive studies to develop a relation for damage spectra, which is a function of the period of vibration, the strength reduction factor, the ultimate ductility capacity of structures, and the site condition (Zhai *et al.* 2013). Zhai *et al.* investigated SDOF systems with different hysteretic models subjected to MA-AF sequences with different levels of PGA_{as}/PGA_{ms} (Zhai *et al.* 2014). Song *et al.* studied the effect of duration and frequency content of the aftershocks on the collapse risk of damaged SDOF systems. Their studies showed that both parameters have significant influence on the collapse risk of the damaged structures (Song *et al.* 2014). Goda *et al.* investigated different aspects of the aftershocks by analyzing a set of SDOF systems with different features under a large database of Japanese earthquakes (Goda *et al.* 2015). Duracan and Duracan proposed an equation to evaluate inelastic displacement ratio of SDOF structure under near-fault seismic sequences (Duracan and Duracan 2016). In the proposed equation, system features and the effect of the frequency content of design earthquake is considered by using the peak ground motion acceleration to peak ground motion velocity ratio. Yaghmaei and García evaluated the nonlinear response of SDOF systems subjected to the earthquakes occurred in Varzaghan and Ahar in 2012 and compared the results with the predicted capabilities obtained from the equation proposed by Hatzigeorgiou. Also, they investigated the energy distribution and the frequency content of the mentioned earthquakes (Yaghmaei and García 2016). Zhang *et al.* carried out extensive studies and accordingly proposed an empirical equation for strength reduction factor, considering MA-AF sequence effects (Zhang *et al.* 2017).

Following these studies, some studies on the effects of seismic sequences on MDOF structures are briefly discussed about. Fragiacomo *et al.* showed the reduction in behavior factor under seismic sequences by carrying out extensive studies (Fragiacomo *et al.* 2004). Lee and Foutch evaluated the performance of steel buildings subjected to seismic sequences (Lee and Foutch 2004). García *et al.* investigated the performance of highway bridges under seismic sequences. Their studies indicate that maximum of drift, and residual drift of highway bridges under considerable aftershocks can increase (García *et al.* 2008). Hatzigeorgiou and Liolios analyzed eight regular and irregular reinforced concrete frames subjected to 5 as-recorded (As-recorded seismic sequences mean that they were recorded on the station during the real successive earthquake occurrence) and 40 artificial seismic sequences using incremental dynamic analysis method. This investigation showed that the seismic sequences lead to increased local and global damage (Park-Ang damage index) and drift demand (Hatzigeorgiou and Liolios 2010). Seismic behavior of steel moment frames and plane concentrically X-braced steel frames subjected to as-recorded seismic sequences were studied by Hatzigeorgiou and Beskos (2012). Their investigation showed that the seismic sequence Phenomenon increases displacement demand, permanent displacement, and other damage indices. García *et al.* evaluated the effect of the MA-AF sequence on maximum of drift and residual drift demand of Structures. Moreover, they studied the frequency content of as-recorded mainshocks and aftershocks, and the results showed that the frequency content of real mainshock and main aftershocks is different. A comparision of the investigated models response to real and artificial seismic sequences demonstrated that artificial MA-AF sequences especially the ones simulated by back-to-back method lead to overestimating peak and residual drift demands of investigated models subjected to seismic sequences (Ruiz-García and Negrete-Manriquez 2011, Ruiz-García 2012). Ryu *et al.* proposed a method to develop fragility curves for damaged structures (Ryu *et al.* 2011). Loulelis *et al.* argued that cumulative damage subjected to successive earthquakes can be estimated by considering the damage a single earthquake brings about (Loulelis *et al.* 2012). Zhang *et al.* studied the local and global damage of concrete gravity dams subjected to as-recorded MA-AF sequence, and the results showed that considering the effects of successive ground motions has a significant effect on the design of concrete gravity dams (Zhang *et al.* 2013). Faisal *et al.* showed that ductility demand of 3D RC frames increases to 1.3 and 1.4 times under double and triple ground motions (Faisal *et al.* 2013). Efraimiadou *et al.* studied the effect of the seismic sequences on RC building frames, considering adjacent buildings effects (Efraimiadou *et al.* 2013). García investigated a three-storey steel office building subjected to different types of seismic sequences (far-field mainshock and near field aftershock, near field mainshock and far field aftershock, etc with different directions). The results of this study showed that drift demand depends on the direction of the mainshock and aftershock, and successive ground motions including far field mainshock and near field aftershock are considered the most critical type of seismic sequence (García 2013). A few investigations have been done on the effect of seismic sequence on bridges. Huang and Andrawes investigated the behavior of Shape Memory Alloy retrofitted bridge subjected to seismic sequences (Huang and Andrawes 2014). Hatzigeorgiou and Hatzivassiliou investigated the three-dimensional reinforced concrete structures subjected to seismic sequences. They investigated 3 and 5 stories regular and irregular in height structures subjected to recorded seismic sequences. Their investigation showed that the displacement, residual displacement, maximum interstory drift ratio, residual interstory drift ratio, and ductility demand significantly increase under seismic sequences (Hatzigeorgiou and Hatzivassiliou 2015). Tang *et al.* studied the effects of seismic sequences on the performance of steel bridges (Tang *et al.* 2016). Hosseinpour and Abdelnaby have recently investigated the effects of earthquakes direction, aftershock polarity, and the vertical component of earthquakes on the response of structures. This investigation showed that the irregularity of the structures, earthquakes direction (for irregular

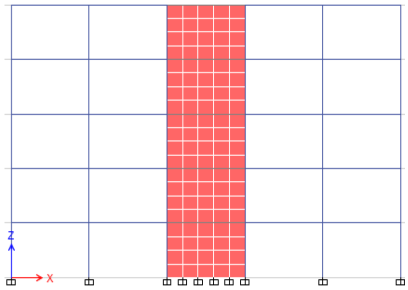


Fig. 1 The configuration of the 5 story model

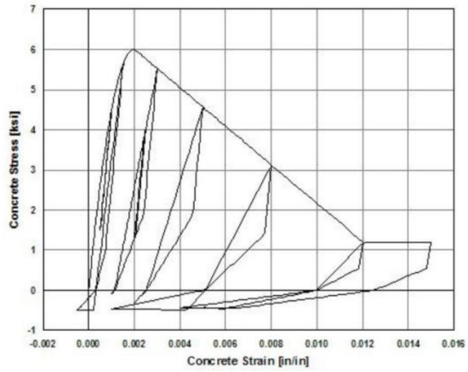


Fig. 2 Typical hysteretic behavior of Concrete 02 material (OpenSees 2008)

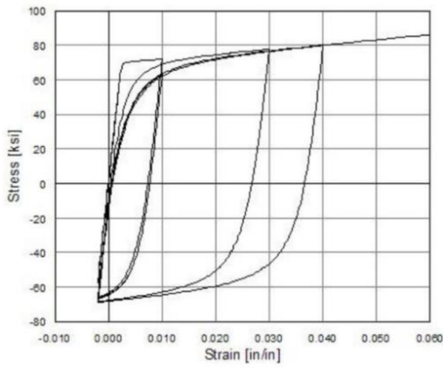


Fig. 3 Typical hysteretic behavior of Steel02 material without isotropic hardening (OpenSees 2008)

structures) and the vertical component of earthquakes have a significant effect on the response of structures and should be considered on designing structures subjected to seismic sequence (Hosseinpour and Abdelnaby 2017). As mentioned, previous studies on the effects of seismic sequences on the structures showed that these effects are significant, and it is necessary that different types of structures subjected to these sequences be studied thoroughly. But the effects of seismic sequences on RC dual shear wall-frame systems have not been investigated yet. This research gap made the writers of this article study the performance of this type of structures under MA-AF sequence.

In this study, to investigate dual shear-wall frame structures, four models of varying heights were designed according to the fourth Iranian Code of Practice for the seismic resistant design of the building and Iranian national building codes (part 9: design construction of the reinforced concrete building). The models were analyzed under 15 as-recorded mainshocks and 15 as-recorded aftershocks, using incremental dynamic analysis method, and the effects of seismic sequences on the structural capacity of the models were investigated by using the IDA curves. Also, the models fragility and vulnerability curves were developed and compared in two states.

2. Models

Four models of varying heights with structural system of combined intermediate shear wall and frame have been investigated in this study as mentioned. According to Hazus-MH definition, a 3-story model and a 5-story one were chosen as the representatives of low rise and mid rise respectively, and two high-rise models having 10 and 15 stories were investigated. Fig. 1 shows the configuration of the 5-story model. The 3, 10 and 15-story models have the similar configurations.

The models were designed according to the requirement of the fourth edition of the Iranian Code of Practice for Seismic Resistant Design of Buildings and Iranian National Building Codes (Part 9: Design and construction of reinforced concrete buildings). It is assumed that the designed structures locating in highly seismic zones of Iran. The analytical process was carried out by OpenSees software, the open system for earthquake engineering simulation. In the next part, the analytical modeling details are explained.

2.1 Analytical modeling

The investigated structures were analyzed by OpenSees software. The distributed plasticity approach was applied for structure modeling. Beams and Columns were modeled by force-based fiber elements, and Shear walls were modeled with displacement-based fiber elements.

Concrete 02 and Steel 02 material were used to build all the fiber sections in either examined structure modeling or investigation structures modeling. Steel 02 is used to construct a uniaxial Giuffre-Menegotto-Pinto steel material. Concrete 02 is used to construct a uniaxial tensile strength and linear tension softening concrete Fig. 2 and Fig. 3 show the hysteretic behavior of Concrete 02 and Steel 02 material.

Multiple elements were used for each story and bay to model the shear walls (Kheyroddin and Naderpour 2008, Esmaeili *et al.* 2013, Ahmadi *et al.* 2017). Fig. 4 shows the modeling details of the investigated structures in the OpenSees.

2.2 Verification

The analytical modeling method has been validated by an experimental sample that was tested on the shack table at NCREE (Hsu and Mo 2010). The specimen was subjected to a seismogram recorded during Taiwan earthquake 1999 at tcu078Eji station. Fig. 5 shows the configuration of the tested model. The experimental data was obtained from the

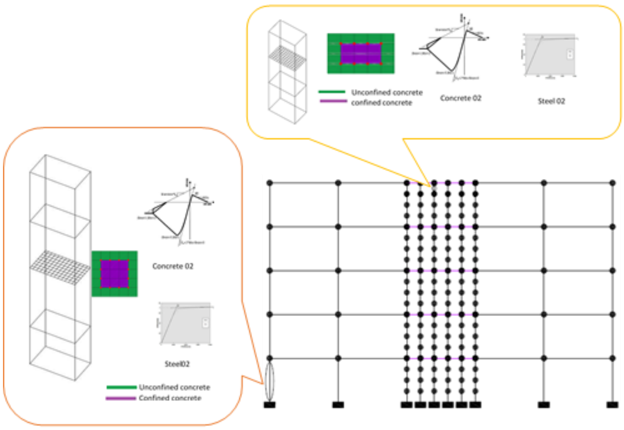


Fig. 4 The built model in the OpenSees

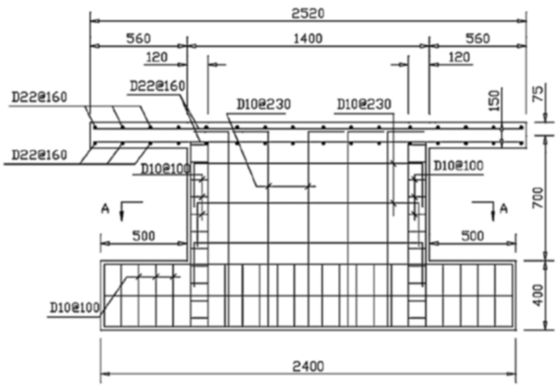


Fig. 5 The verification model (Hsu and Mo 2010)

figures given in the mentioned reference by using WebPlotDegitizer tool (Rohatgi 2011). As shown in Fig. 6, the response of the experimental sample and the analytical model reasonably match.

3. Incremental dynamic analysis

Incremental dynamic analysis method proposed by Vamvatsikos & Cornell (2002) was used to analyze the structures in this study. This method is one of the most accurate methods to analyze structures (Khatami *et al.* 2019). IDA curves perfectly show the structural behavior under the input ground motion. To carry out IDA, two parameters as the representative of ground motion intensity and damage intensity should be selected. In this study, spectral acceleration and the maximum interstory drift ratio were selected as the representatives of seismic intensity and structural damage intensity respectively (Mirrashid 2017). Since spectral acceleration depends on both structure and ground motion record, it's an appropriate earthquake intensity measure. The second reason is that structures with first-mode dominated is sensitive to the strength of the frequency content near its first-mode frequency, which is well characterized by spectral acceleration (Vamvatsikos and Cornell 2002).

3.1 Incremental dynamic analysis of damaged structures

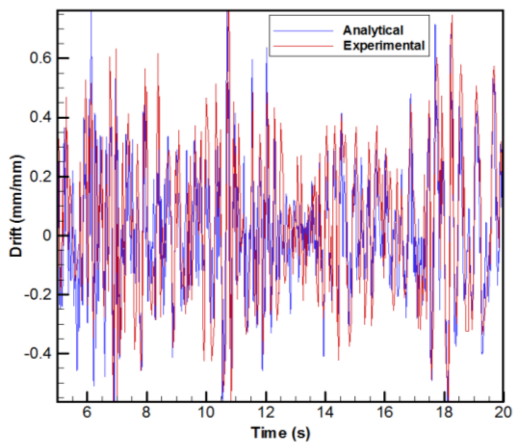


Fig. 6 Experimental and analytical drift time history of the specimen

To perform IDA for structures subjected to seismic sequences, the most important challenge is the simulation of the structures damaged by mainshock. To simulate a damaged structure, two approaches can be seen in technical literature. According to the first approach, proposed by Ryu *et al.* (2011), a determined damage level for the investigated structure at the end of the mainshock is assumed. The numerical value of the intensity measure corresponding to assumed damage level can be considered a deterministic or uncertain amount. According to the second approach, used by Raghunandan *et al.* (2015), different levels of damage are considered for the structure at the end of the mainshock ground motion. In this study, the first approach has been applied to simulate the damage to structures caused by mainshock. Since moderate aftershocks usually occur after moderate to strong mainshocks, and because the major objective of this study is to estimate the collapse risk of damaged structures subjected to aftershocks, it is assumed that the investigated structures reach the extensive damage (ED) level according to the Hazus-MH definition. By performing IDAs for all investigated models under 15 mainshocks, IDA curves for the structures subjected to mainshocks were developed, and an appropriate scale factor for each mainshock was calculated to simulate the structures damaged by mainshock was assumed to have reached the extensive damage level. So the applied seismic input in each step of IDA of the structure subjected to MA-AF contains the scaled mainshocks to make the structure reach the extensive damage level under the mainshock, a time gap of 20s to cease the structural vibration, and aftershock.

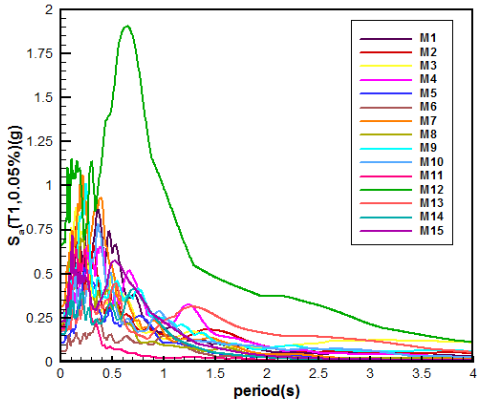
3.2 Ground motion records

Generally, as-recorded or artificial seismic sequences are used to study the structures subjected to MA-AF sequence. Two approaches are employed to simulate artificial seismic sequences. The first is a back-to-back method in which the mainshock or scaled mainshock is repeated as an aftershock. The randomized method is the second. In this method, artificial sequences are generated by selecting the mainshock randomly and repeat it or its scaled

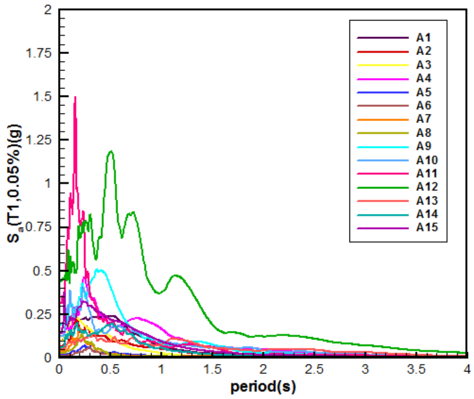
Table 1 The details of the input ground motion records

Name	Symbol*	Moment Magnitude	PGA (g)
Imperial Valley	M1	6.53	0.276
	A1	5.01	0.098
Imperial Valley	M2	6.53	0.203
	A2	5.01	0.066
Imperial Valley	M3	6.53	0.222
	A3	5.01	0.096
Northridge	M4	6.69	0.193
	A4	5.93	0.13
Northridge	M5	6.69	0.109
	A5	5.93	0.016
Northridge	M6	6.69	0.06
	A6	5.93	0.011
Northridge	M7	6.69	0.316
	A7	5.93	0.036
Northridge	M8	6.69	0.213
	A8	5.93	0.026
Chalfant valley	M9	6.19	0.248
	A9	5.44	0.187
Chalfant valley	M10	6.19	0.175
	A10	5.44	0.124
Petrolia	M11	7.2	0.176
	A11	6.7	0.313
Petrolia	M12	7.2	0.662
	A12	6.5	0.439
Petrolia	M13	7.2	0.178
	A13	6.5	0.051
Whittier Narrows	M14	5.99	0.155
	A14	5.27	0.061
Whittier Narrows	M15	5.99	0.229
	A15	5.27	0.139

*M represent mainshock and A represent aftershock



(a)



(b)

Fig. 7 5% damped elastic acceleration spectra of input ground motions: (a) Mainshocks; (b) Aftershocks

acceleration time history to simulate the aftershocks. The frequency content of the utilized main-shock to generate the aftershock do not change in this simulation method. According to the previous studies, the frequency content of the mainshock and main aftershock is different, and using artificial seismic sequences may lead to overestimation of the maximum interstory drift demands (Ruiz-García and Negrete-Manriquez 2011). Therefore, as-recorded seismic sequences were applied in this study. A number of as-recorded MS-AS sequences are selected and employed as ground motions. A mainshock generally is followed by a number of aftershocks. The best way to evaluate the effect of MS-AS is considering all corresponding aftershocks. However, this would be too time consuming. Thus only a single largest aftershock was used in a real MS-AS sequence in this investigation. 15 as-recorded MA-AF include the 1979 Imperial Valley, the 1986 Chalfant Valley, the 1987 Whittier Narrows, the 1992 Petrolia, and the 1994 Northridge Earthquakes, were selected to investigate the performance of the models subjected to MA-AF sequence. The site condition of all selected seismic sequences is similar and the average of the shear wave velocity in upper 30 meters is 180 m/s to 360 m/s. according to fourth Iranian Code of Practice for the seismic resistant design of the building, all record stations locate on third type soil. Soil conditions at the record stations and the assumption in the design procedure are the same (Vaez *et al.* 2013). Ground motions data taken from databases including the Center for Engineering Strong Motion Data (CESMD) and the Pacific Earthquake Engineering NGA Database (PEER NGA) were downloaded. The moment magnitude of the selected mainshocks and the aftershocks vary from 5.99 to 7.2 and 5.01 to 6.7 respectively.

The criteria to select seismic sequences are:

(a) The selected aftershock is one with the largest magnitude among the aftershocks following the mainshock.

(b) Each seismic sequence contains the mainshock and an aftershock recorded in the same station.

(c) This study focused on the effects of far-field seismic sequences, so the source-to-site distance of selected mainshocks and aftershocks is larger than 10 km.

(d) The site condition of all selected seismic sequences is similar and the average of shear wave velocity in upper 30 meters is 180 m/s to 360 m/s.

The details of the all MS-AS sequences are presented in Table 1, and their elastic acceleration spectra has been shown in Fig. 7.

4. Developing fragility curves

Fragility curves are strong measures that present a relationship between seismic intensity and probability of a specified damage state to exceed. In Hazus-MH, 5 damage state including none, slight, moderate, extensive and complete are defined. Since the major objective of this study is estimating the collapse risk of structures under seismic sequences, fragility curves at complete damage state were developed for intact and damaged structures. A lognormal cumulative distribution form is usually assumed for the fragility function. Eq. (1) presents the mentioned form of fragility function (Hazus 2001)

$$P[ds|S_a] = \Phi\left[\frac{1}{\beta_{ds}}\ln\left(\frac{S_a}{\bar{S}_{a,ds}}\right)\right] \tag{1}$$

Where Φ is the standard normal cumulative distribution function, $\bar{S}_{a,ds}$ and β_{ds} is the median value and standard deviation of spectral acceleration at which the threshold of the intended damage state, ds, reaches.

For mainshock damaged structures, fragility curves were developed according to equation 2 proposed by Ryu *et al.* (2011) and lognormal distribution assumption for fragility function.

$$\begin{gathered} P(DS_a > ds_a|\mathrm{IM}_a = im_a, DS_m = ds_m) = \\ P\big(DS_a > ds_a\big|IM_a = im_a, EDP_m = mDST_{ds,m}\big) \end{gathered} \tag{2}$$

Where, DS_a is damage state at the end of the aftershock. DS_m is damage state at the end of the mainshock. EDP_m is the response of the structure to the mainshock and IM_a is intensity of the aftershock.

5. Developing vulnerability curves

Vulnerability curves are strong tools to predict loss and to make decisions before earthquake occurance, but Fragility curves express the probability of a special damage level to exceed. This is the major difference between fragility and vulnerability curves. Vulnerability function is developed by combining discrete probabilities of the structure to reach the damage levels. According to Hazus-MH, the cumulative probabilities are converted to discrete probabilities by Eqs. (3) to (7). Also, vulnerability function is developed by Eq. (8).

$$P[D_s = ds_1] = 1 - \mathrm{P}[D_s \geq ds_2] = P_1 \tag{3}$$

$$P[D_s = ds_2] = \mathrm{P}[D_s \geq ds_2] - P[D_s \geq ds_3] = P_2 \tag{4}$$

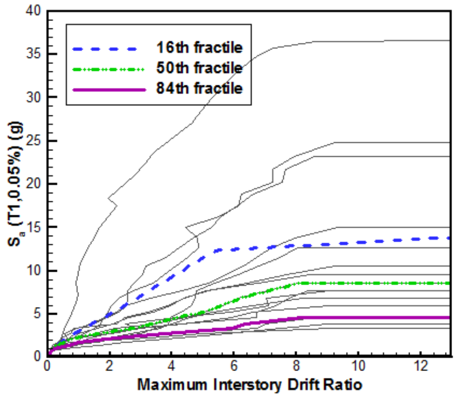
$$P[D_s = ds_3] = \mathrm{P}[D_s \geq ds_3] - P[D_s \geq ds_4] = P_3 \tag{5}$$

$$P[D_s = ds_4] = \mathrm{P}[D_s \geq ds_4] - P[D_s \geq ds_5] = P_4 \tag{6}$$

$$P[D_s = ds_5] = \mathrm{P}[D_s \geq ds_5] = P_5 \tag{7}$$

$$DR_c = \sum_{i=2}^{5} DR_i \times P[ds_i] \tag{8}$$

Where ds_i is the defined damage state (none, slight, moderate, extensive and complete), and DR_i is the mean damage factor of intended damage state.



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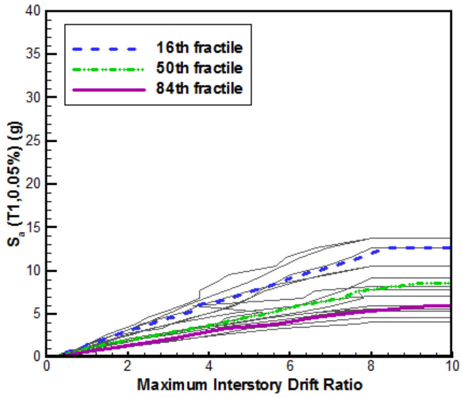

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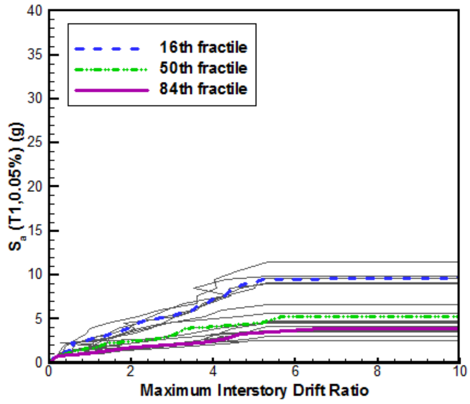

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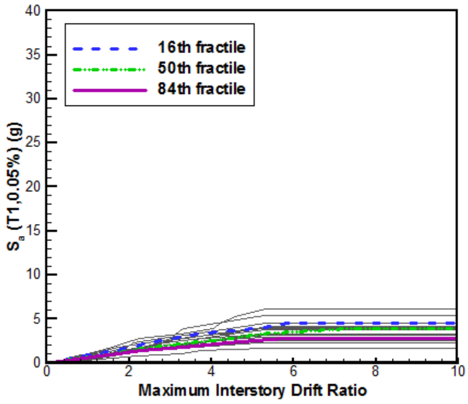


(d)

Fig. 8 IDA curves: (a) 3-story model subjected to mainshock (b) 3-story model subjected to the MA-AF sequence (c) 5-story model subjected to mainshock (d) 5-story model subjected to MA_AF sequence

6. Result and discussion

The investigated models were analyzed by using IDA method under 15 as-recorded mainshocks and 15 MA-AF sequences. Accordingly, the IDA capacity curves were developed, and the effect of the seismic sequences on seismic capacity of the structures was calculated. Also, fragility curves of structures were developed by performing a linear regression analysis of the obtained data. Moreover, the vulnerability curves of the models subjected to mainshock and MA-AF sequence were developed, and accordingly, the effect of the seismic sequences was investigated. There follows the results discussed.

6.1 IDA curves

Fig. 8 and Fig. 9 represent the IDA curves of the investigated models subjected to mainshock and MA-AF sequence. IDA curves represent the structural behavior under input ground motions perfectly. Each IDA curve contains a linear region. In the nonlinear region, the IDA curves have different behavior at the variant seismic intensity. Hardening or softening behavior may be seen in the different ground motion intensity. Moreover, the IDA curves are dependent on the input ground motion strongly. So, summarized IDA curves, i.e., the 16th, 50th, and 84th fractiles were developed for better comparison. As it is seen, there is a significant difference between the seismic capacity of the mainshock damaged models and the intact models. On average, the seismic capacity of 3-story, 5-story, 10-story, and 15-story models decreased by 7.7%, 30%, 51% and 66% respectively under seismic sequence in comparison with the mainshock only. Each model seismic capacity change under MA-AF sequence has been presented in Fig. 14. As it is seen, the effect of the seismic sequences on the seismic capacity of the low-rise model is less than the mid-rise and the high-rise model, and the mid-rise model was less than the high-rise model, which means that taller structures are affected more by seismic sequences effects.

6.2 Fragility curves

The next step is generating fragility curves. For this purpose, the lognormal distribution form was assumed for the fragility function. By performing a linear regression analysis on the obtained data from the IDAs for each model, mean and standard deviation of the spectral acceleration (ground motion intensity measure) was calculated for the intended damage level and accordingly the fragility curves were developed. The results of the regression analyses are presented in Fig. 10. According to equations presented in the previous section, fragility curves were developed. The fragility curves for Extensive and Complete damage level of the investigated models subjected to mainshock are presented in Fig. 11 respectively. To investigate the effect of seismic sequence on the probability of exceedance Complete damage level for the models subjected to mainshock and MA-AF sequence are presented in Fig. 12. It can be seen clearly that the collapse probability of the investigated structures is increased significantly under

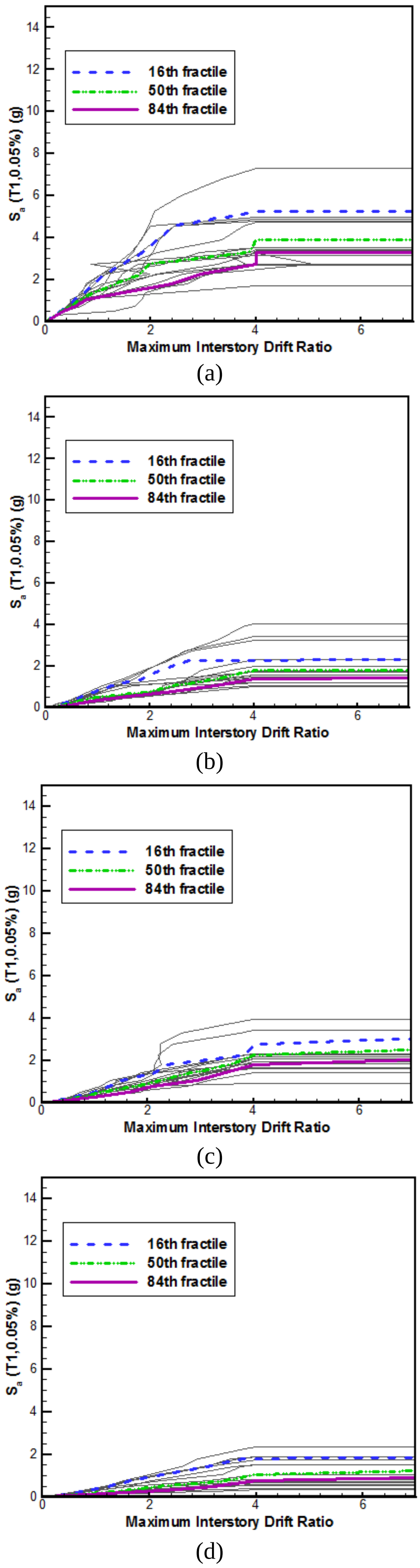


Fig. 9 IDA curves: (a) 10-story model subjected to mainshock (b) 10-story model subjected to the MA-AF sequence (c) 15-story model subjected to mainshock (d) 15-story model subjected to MA_AF sequence

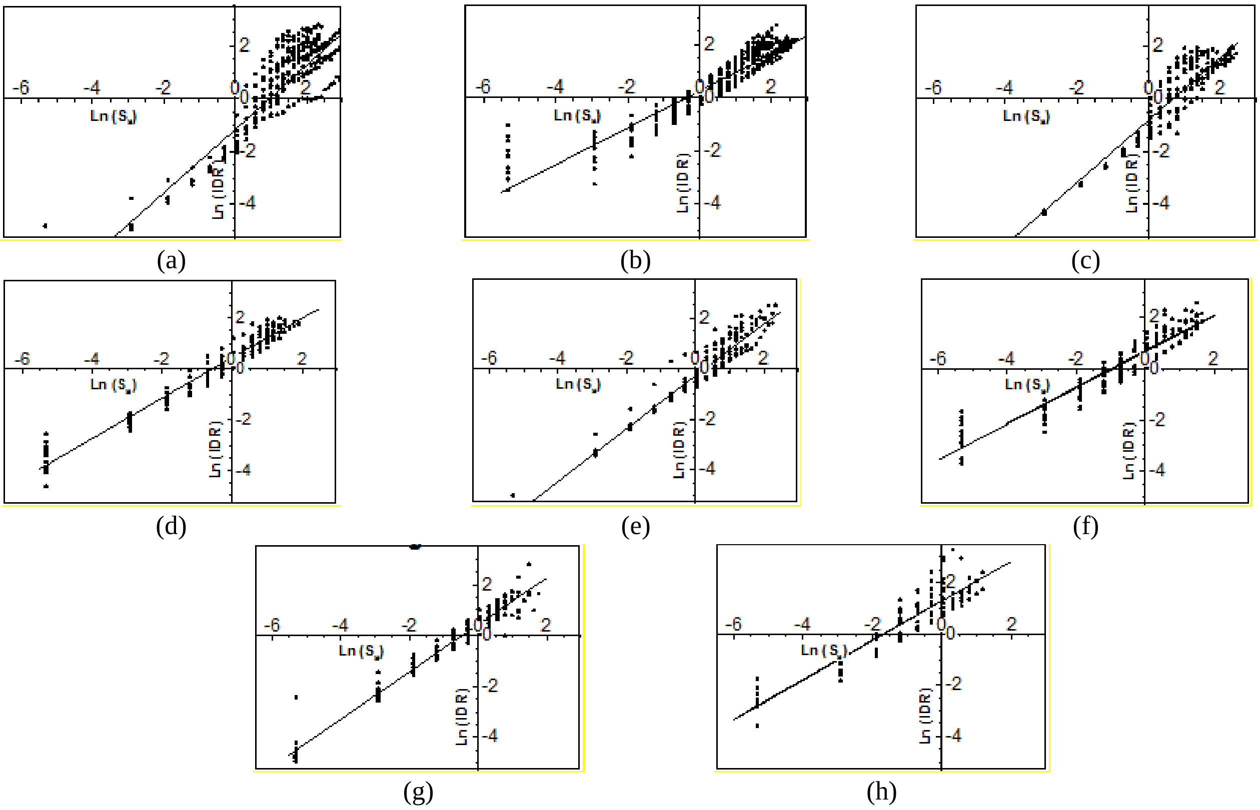


Fig. 10 Lognormal Probability plot for collapse probability curve: (a) 3-story model subjected to mainshock (b) 3-story model subjected to MA-AF sequence (c) 5-story model subjected to mainshock (d) 5-story model subjected to MA_AF sequence (e) 10-story model subjected to mainshock (f) 10-story model subjected to MA-AF sequence (g) 15-story model subjected to mainshock (h) 15-story model subjected to MA_AF sequence

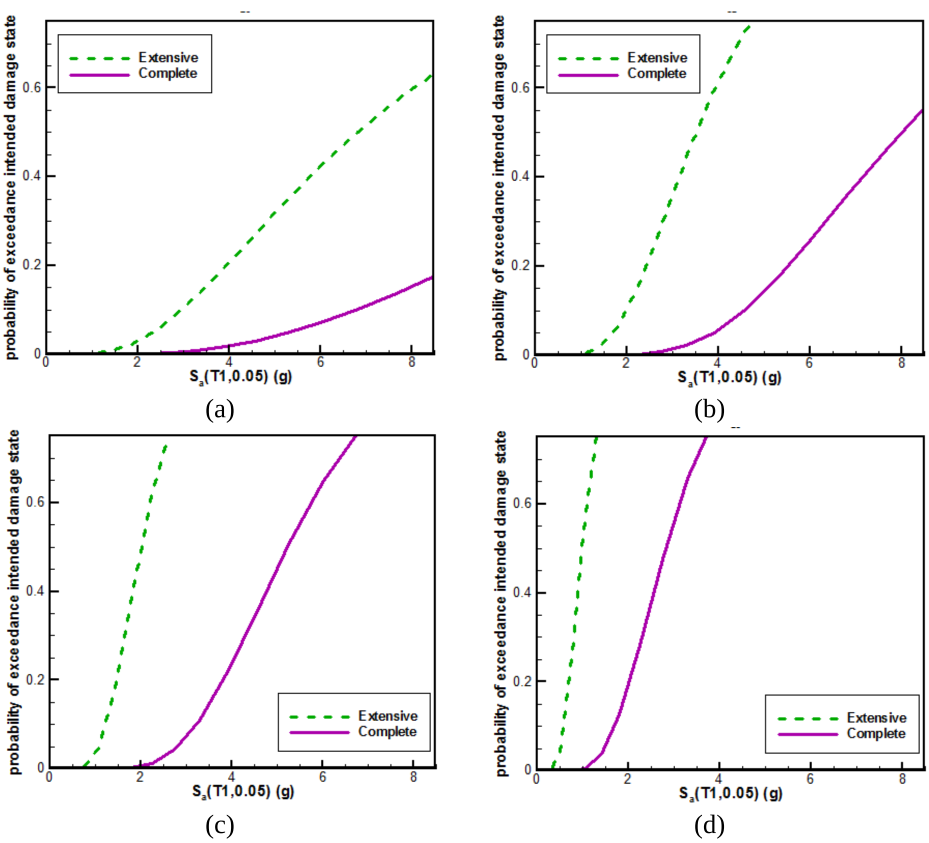


Fig. 11 Extensive and collapse fragility curves of the models subjected to mainshock: (a) 3-story model (b) 5-story model (c) 10-story model (d) 15-story model

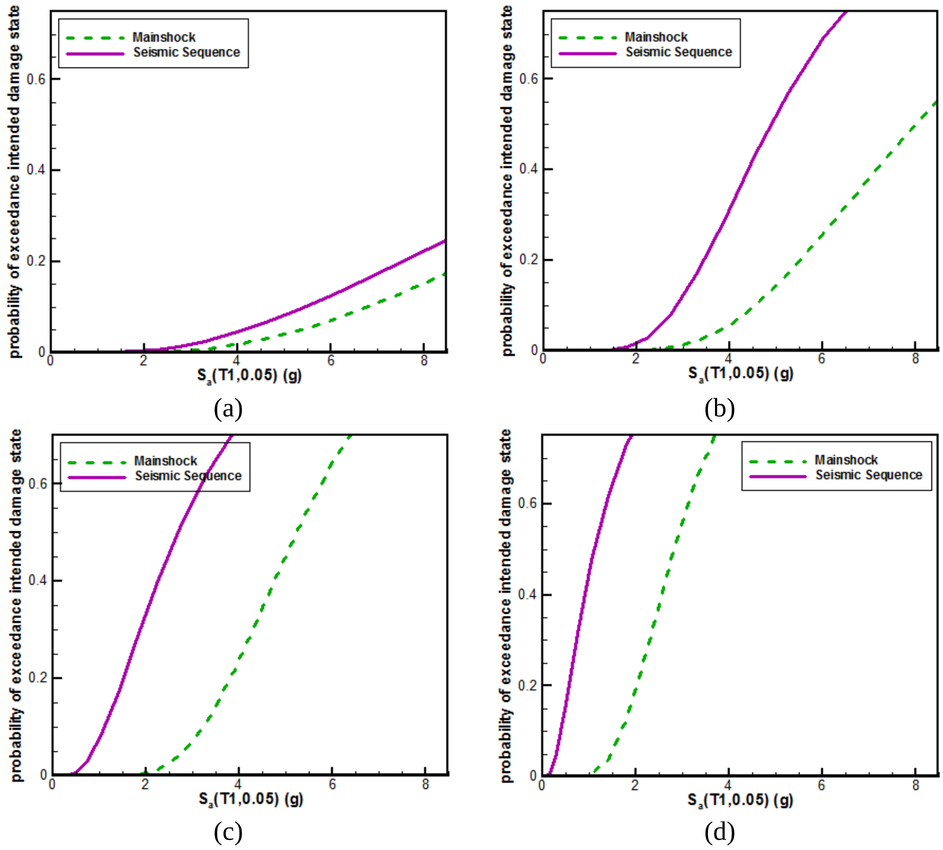


Fig. 12 Comparison of collapse fragility curves of the models subjected to mainshock and MA-AF sequence: (a) 3-story model (b) 5-story model (c) 10-story model (d) 15-story model

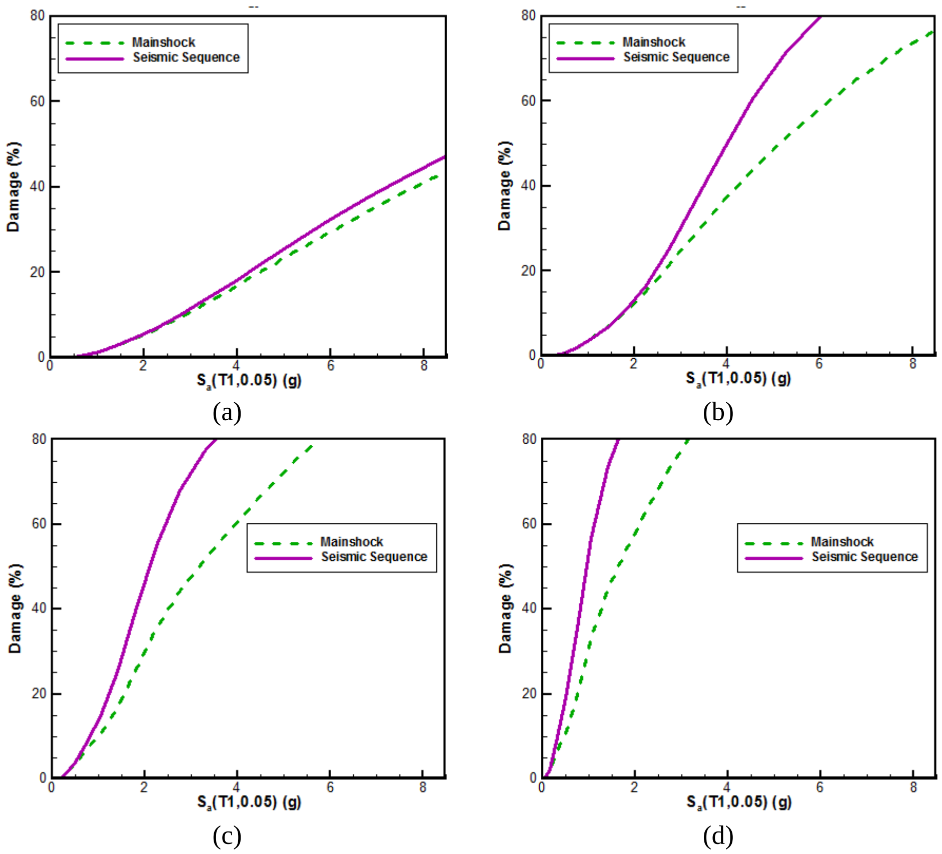
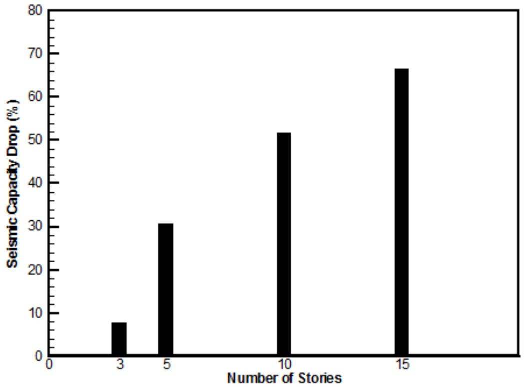
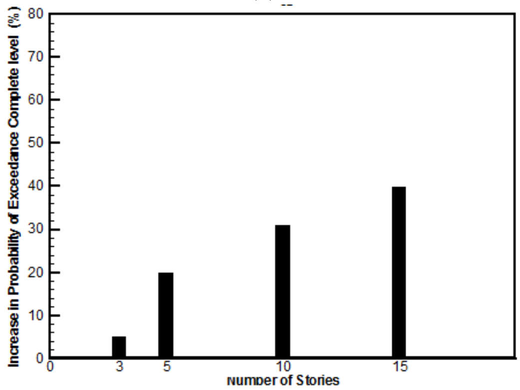


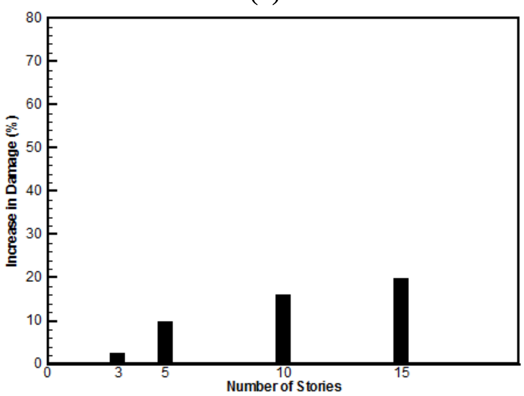
Fig. 13 Comparison of vulnerability curves of the models subjected to mainshock and MA-AF sequence: (a) 3-story model (b) 5-story model (c) 10-story model (d) 15-story model



(a)



(b)



(c)

Fig. 14 (a) Comparison of seismic capacity of the models with and without seismic sequence effects consideration (b) Comparison of probability of exceedance collapse level with and without seismic sequence effects consideration (c) Comparison of damage percent induced by mainshock and MA-AF sequence

seismic sequence in comparison with a mainshock ground motion only. For better comparison, an average of the probability of exceedance complete level for each investigated model under the seismic sequence in comparison with the mainshock ground motion only is presented in Fig. 14. As can be seen, the collapse probability of the 3-story, 5-story, 10-story and 15-story models under MA-AF sequence are increased 5%, 19%, 30%, and 39% respectively in comparison with the models subjected to the mainshock only. The same as the structural capacity, the effect of the seismic sequences on the collapse probability of the higher structures is stronger.

6.3 Vulnerability curves

In this section, the loss is calculated by developing the vulnerability curves which are strong tools to evaluate the loss during earthquakes. The vulnerability curves were developed for each model under two types of input ground motions. The vulnerability functions were developed according to equation 3 to 7. For comparison, the developed vulnerability curves of the models under two types of input seismic sequences have been presented in Fig. 13. As it is seen, the seismic sequences effects make the models more vulnerable. Fig. 14 presented the effect of MA-AF sequence on the loss level of the models during earthquakes. The loss level of the 3-story, the 5-story, the 10-story, and 15- story models under MA-AF sequence increases by 2.5%, 9.9%, 16% and 19.9% respectively.

7. Conclusions

This paper studies the effects of the mainshock-aftershock sequences on the two dimensional frames with reinforced concrete dual shear wall-frame systems. For this purpose, a low-rise structure, a mid-rise, and two high-rise structures were designed according to the requirements of the fourth Iranian Code of Practice for the seismic resistant design of the building and Iranian national building codes (part 9: design construction of the reinforced concrete building). The structural capacity of the models under MA and MA-AF sequences was investigated by performing IDA of the models under 15 MA and 15 MA-AF. Moreover, the fragility and vulnerability curves for each model were developed for two types of input ground motions. This study has led to the following conclusions:

- Developed IDA curves show that the effects of the seismic sequences lead to 7.7%, 30%, 51%, and 66% decrease in the structural capacity of 3, 5, 10, and 15-story models respectively.
- According to the fragility curves, the collapse probability of the 3, 5, 10, and 15-story models under MA-AF sequence, in comparison with the mainshock only, increases by 5%, 19%, 30% and 39% respectively.
- Vulnerability curves observations show that seismic sequences result in bigger amount of loss. The average increase in loss is 2.5%, 9.95%, 16%, and 21.76% in low-rise, mid-rise, and high-rise models respectively.
- The effects of seismic sequences on taller structures are bigger

The results of this study show that seismic sequences have a significant effect on the dual shear wall frame structures; therefore, it is necessary to modify construction and building design regulations, considering the effects of the seismic sequences.

It is suggested that the effect of seismic sequences on three dimensional structures with similar structural systems be investigated in future studies. Also, it is recommended that irregular structures be studied in future research programs.

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